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FAILURE ANALYSIS OF A MAIN ROTOR PITCH HORN BOLT LOCATED ON THE AH-1 COBRA HELICOPTER

VICTOR K. CHAMPAGNE, Jr.
MATERIALS TESTING AND EVALUATION BRANCH

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ABSTRACT

A comprehensive metallurgical examination of the pitch horn bolt was conducted at the U.S. Army Materials Technology Laboratory (MTL) to determine the probable cause of failure. The component is part of the main rotor hub assembly and had failed while in service.

Light optical microscopy revealed evidence of corrosion pitting in regions adjacent to the fracture. Chemical analysis verified that the part was fabricated from 4340 steel. It was determined by metallographic examination that the microstructure was tempered martensite. Hardness measurements taken on transverse cross sections of the bolt near the fracture indicated that the material had been hardened to the upper limit of the specified range. The surface finish was measured along the upper shank and conformed to the requirements of the engineering drawing. Fractographic examination utilizing the scanning electron microscope (SEM) revealed multiple crack origins which assumed a "thumbnail" shape and displayed surface morphologies which resulted from intergranular decohesion. Many of these crack sites were initiated from corrosion pits. Energy dispersing spectroscopy (EDS) performed on areas within the crack initiation site showed the presence of chlorides. Beyond the thumbnail zone fast fracture occurred in a ductile manner, which was confirmed by a dimpled topography. The failure was attributed to stress corrosion cracking (SCC).

CONTENTS

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A-1

BACKGROUND

The Aviation Systems Command (AVSCOM) Depot Engineering and Reliability Centered Maintenance Support Office located at Corpus Christi Army Depot requested that MTL perform a failure analysis of the pitch horn bolt which had failed during service. The failure was discovered upon disassembly of the component during a maintenance procedure. The bolt is part of the Main Rotor Hub Assembly located on the AH-1 Cobra Helicopter, as depicted in Figure 1. The general arrangement of the assembly components relative to the main rotor system can be viewed in detail in an enlarged illustration of this area contained in Figure 2. The torque requirements for the bolt under investigation (1000 to 1200 in.-lb) along with those for adjacent fasteners have been listed on the schematic. Two pitch horn bolts are inserted into the pitch horn assembly which is a portion of the mechanism that controls the pitch of the helicopter blades during flight, as shown in Figure 3. When one of these bolts fails in service, the load is transferred to the remaining component still intact which drastically reduces its fatigue life. Failure of both pitch horn bolts will prevent the pilot from properly controlling the helicopter during flight and when landing. It is important to note that the only area under applied stress after installation is located beneath the upper shank of the bolt. There is actually a space between the head of the bolt and the bushing, as illustrated in Figure 4, indicating the absence of any externally applied loads in this region.

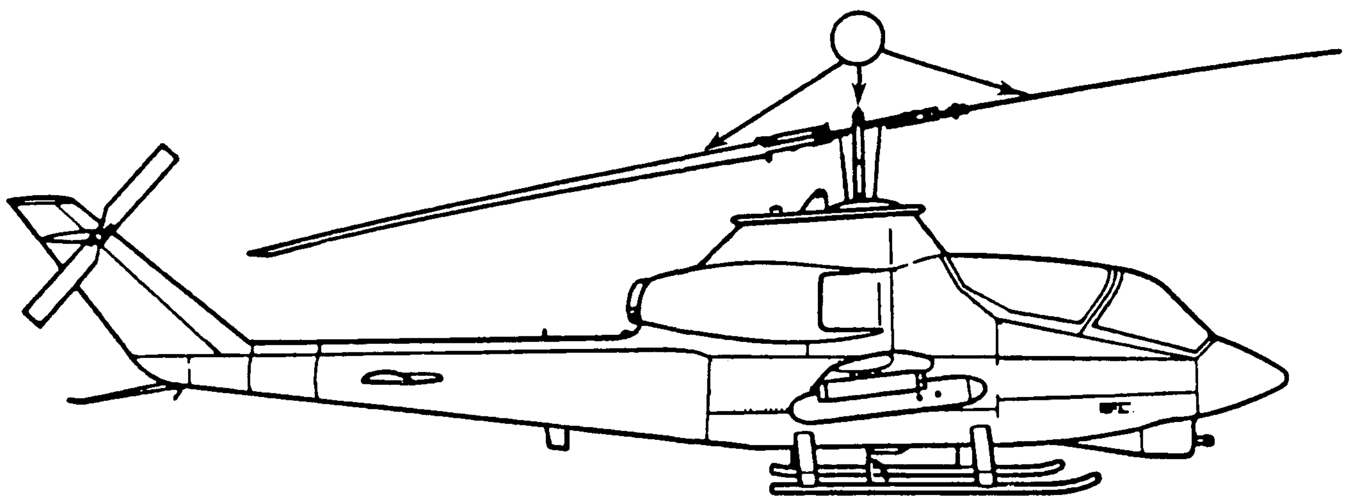


Figure 1. Schematic of the AH-1 Cobra Helicopter showing the general location of the pitch horn bolt.

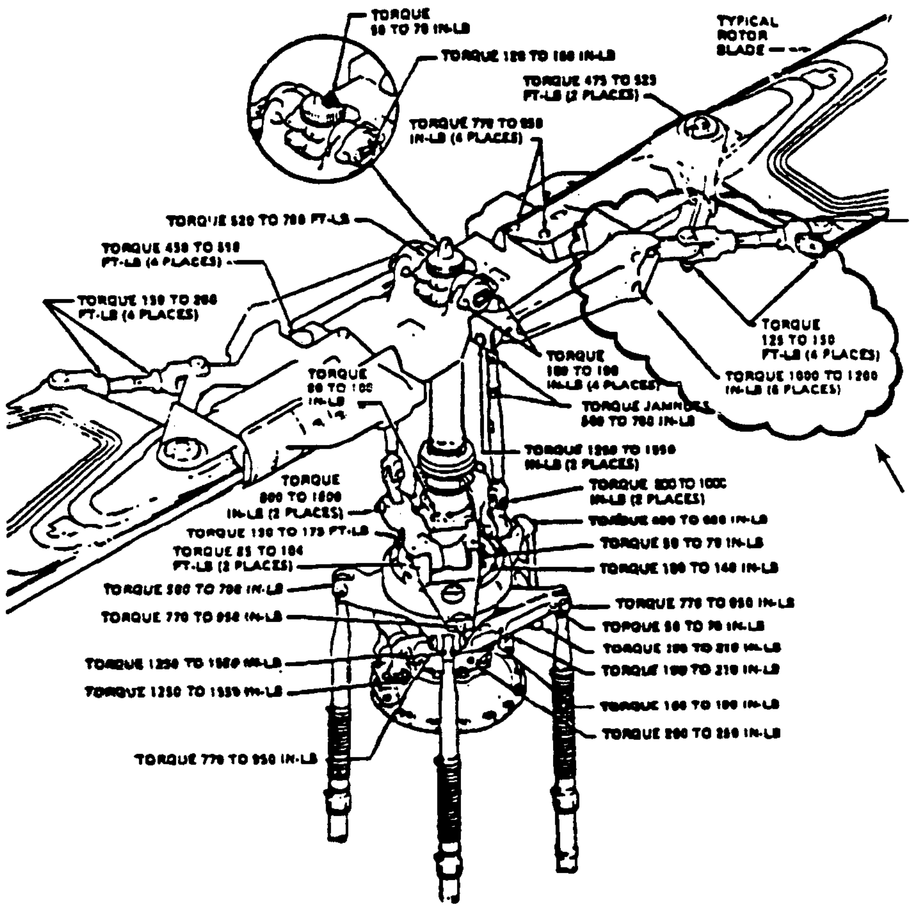
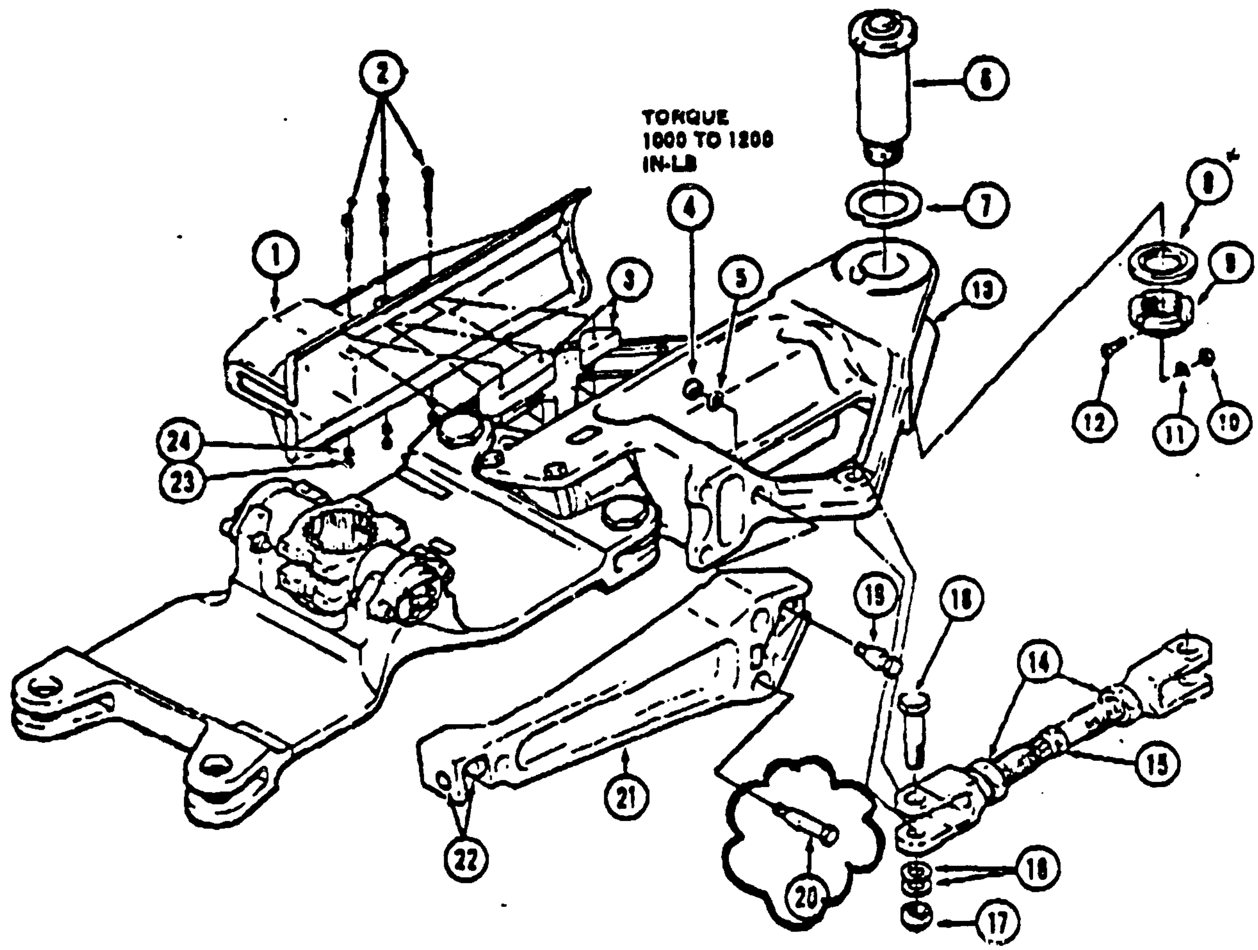


Figure 2. Enlarged view of the Main Rotor Hub Assembly
which contains the pitch horn bolt.



Item No.	Component	Item No.	Component
1.	Sand deflector	13.	Grip
2.	Bolts	14.	Jam nut
3.	Shims (spacers)	15.	Drag brace
4.	Special nut	16.	Steel washers
5.	Special washer	17.	Nut
6.	Bolt assembly	18.	Bolt
7.	Keyway washer	19.	Special Bolt (Pitch Horn Bolt)
8.	Special washer	20.	Special Bolt (Pitch Horn Bolt)
9.	Special nut	21.	Pitch horn assembly
10.	Extended washer nut	22.	Bushings
11.	Steel washer	23.	Nuts
12.	Screw	24.	Washers

Figure 3 Enlarged view of the Main Rotor Hub Yoke Extension and Grip Assembly. The pitch horn bolt is Item 20.

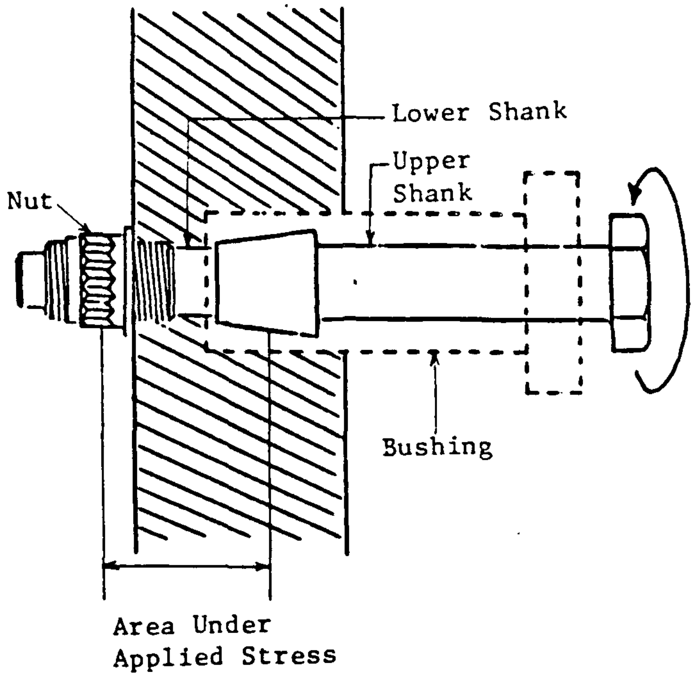


Figure 4. Schematic showing installation of the bolt during service.

Figure 5 contains the engineering drawing of the component which lists some of the manufacturing specifications and inspection criteria. The bolt was required to be fabricated from 4340 steel according to the requirements established in AMS 6414 and subsequently heat treated to attain a tensile strength range of 180 to 200 ksi. The surface finish of the bolt was to be 125 microinches (u in.) root mean square (RMS) with the exception of two areas which were 63 (u in.). The bolt had been designated to receive a cadmium plating which was to be applied by an electrolytic process. The exact age of the component or its time in service could not be determined by Corpus Christi maintenance personnel and AVSCOM engineers, but it was thought to have been installed on the aircraft for at least one year and could be as many as fifteen years old.

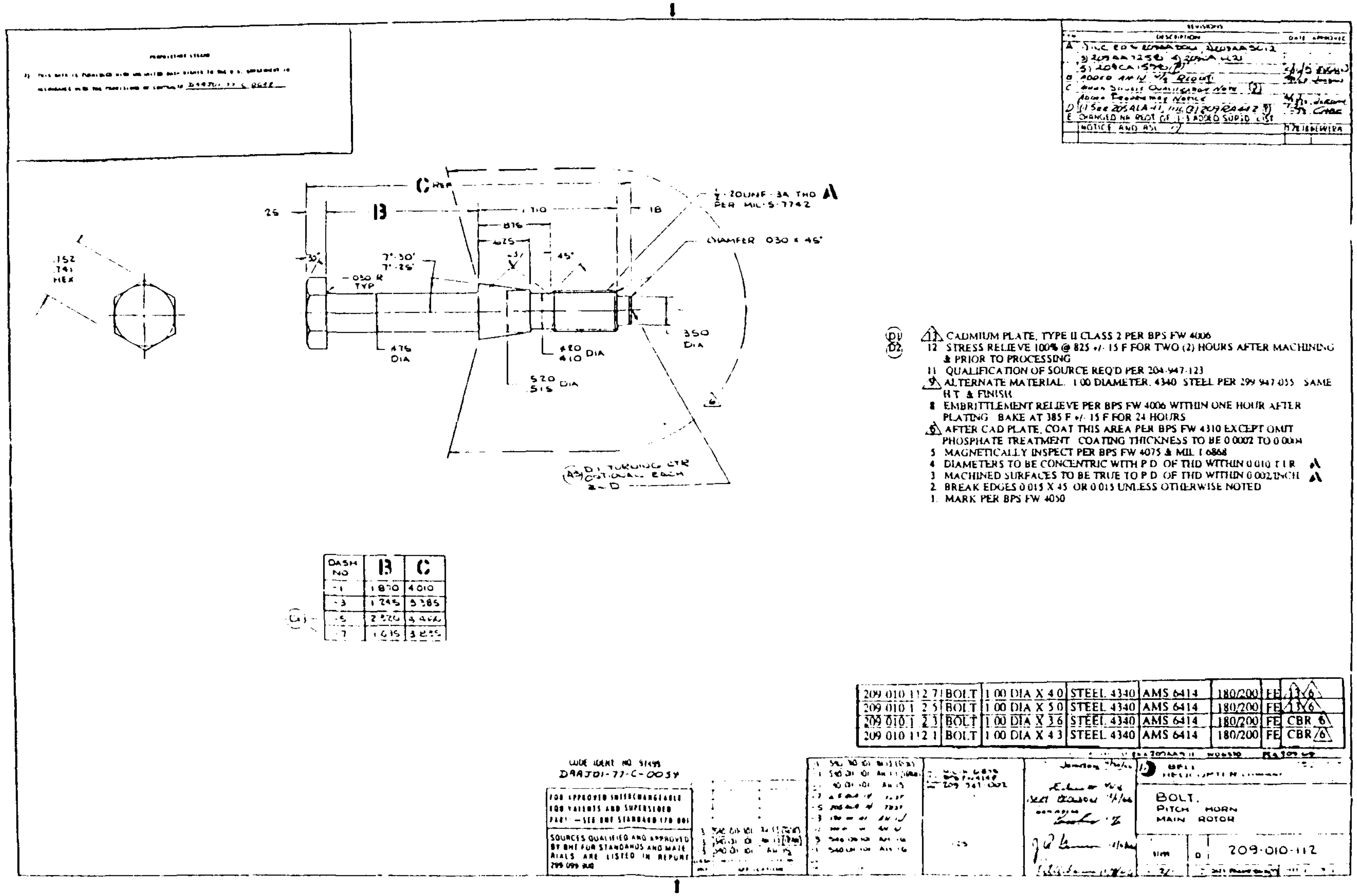


Figure 5 Engineering drawing of the Main Rotor Pitch Horn Bolt

TEST RESULTS

Visual Examination and Light Optical Microscopy

Figure 6 shows the component in the as-received condition. The failure occurred during service where the bolt sheared at the radius located between the conical section of the component and the threads. The conical section located beneath the upper shank was covered with a dry film lubricant. The nut and the remaining threaded portion of the bolt were missing upon disassembly. Figure 7 reveals that a locating hole had been drilled into the top of the bolt head. This information was used to identify the possible manufacturer of the component. Figure 8 represents one of the few areas adjacent to the fracture where the cadmium plating was still intact. In most of the regions surrounding the fracture, the plating had been completely worn away during service. Further examination of surfaces near the failure revealed evidence of corrosion pits, as shown in Figures 9 and 10. Localized attack occurred here because the cadmium plating had been damaged exposing unprotected metal to the environment. Another significant observation made when examining the radius near the fracture, was that deep machining marks had been left on the surface in this area, (refer to Figure 11). Pits can also be seen within the machining marks. Both of these surface defects acted as localized stress concentration areas where cracks initiated and propagated in service.

Figure 6 Macrograph of pitch horn bolt in the as-received condition The arrow identifies the failure site

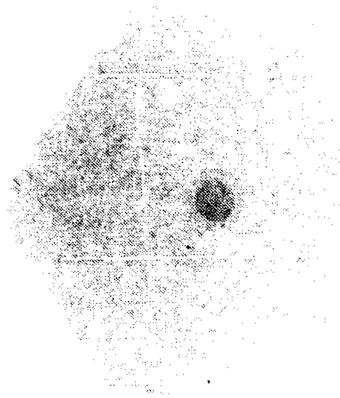


Figure 7. Macrograph of the bolt head showing a drilled locating hole in the center. MAG. 3.5X.

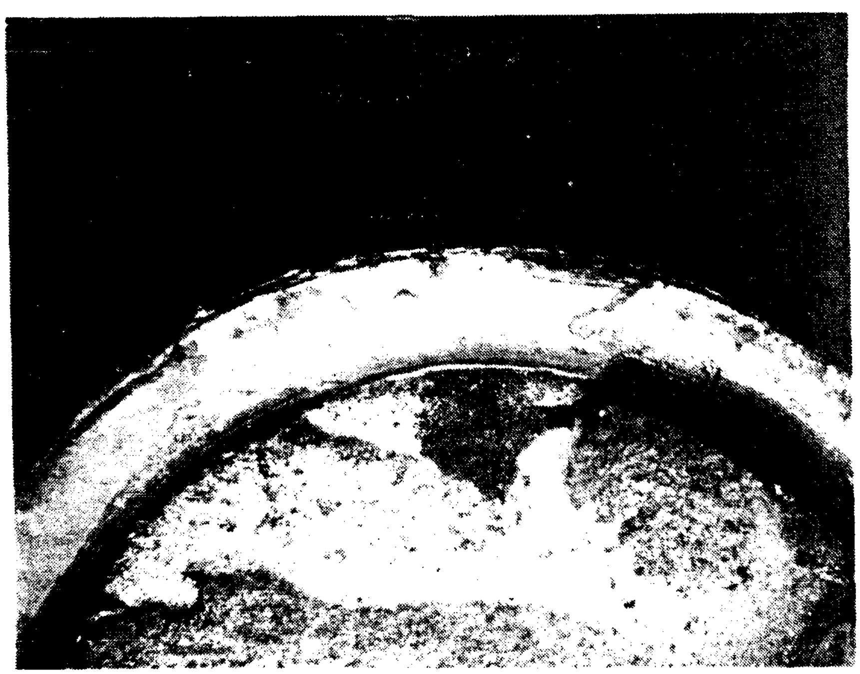


Figure 8. Optical macrograph showing the damaged cadmium plating and evidence of corrosion on the fracture face. MAG. 15X.

Figure 9. Stereoscopic inspection showed corrosion pits on the machined radius adjacent to the fracture (designated by arrows). MAG. 35X.

Figure 10. Closer examination revealed numerous pits in areas adjacent to the fracture where the cadmium plating had completely worn away. MAG. 65X.

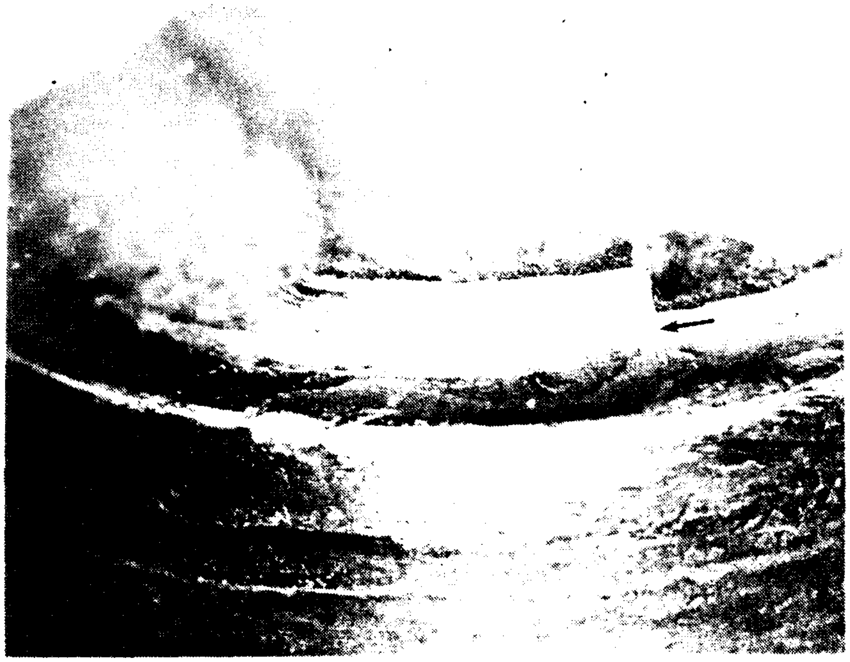


Figure 11. Optical macrograph showing deep machining marks on the radius (identified by the arrow). MAG. 15X.

Surface Finish Measurements

A Mitutoyo Surftest Analyzer was used to measure the surface finish of the pitch horn bolt. The instrument was calibrated with a Bendix Precision Roughness Standard (Model No. 25A). A total of three measurements were taken 120° apart from each other along the upper shank of the component, within regions that had not experienced wear during service, as shown in Figure 12. Further measurements of other surfaces could not be performed because of excessive service-related wear. Bell Helicopter Drawing No. 209-010-112 specified the surface finish of the bolt to be 125 microinches (u in.) RMS except for two areas where the finish was required to be 63 (u in.), as identified in Figure 13. For each measurement, five consecutive sample lengths of 0.03 in., were taken in a line parallel to the bolt's center-line to arrive at a representative RMS value. The three results of 68 u in., 64 u in., and a 70 u in. were within the drawing requirements. A representative plot of the topography transversed by the profilometer's needle during each measurement is shown in Figure 14. The data obtained from this test is listed in Table 1.

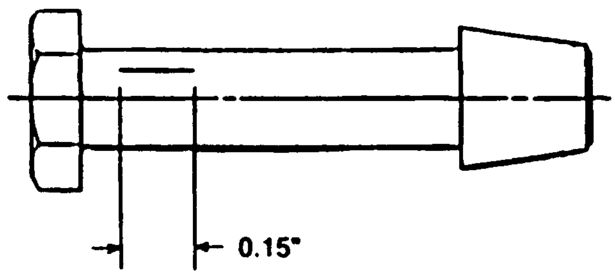


Figure 12. Schematic showing where surface profile readings were taken. Three measurements were taken along the same general portion of the bolt, approximately 120° from each other.

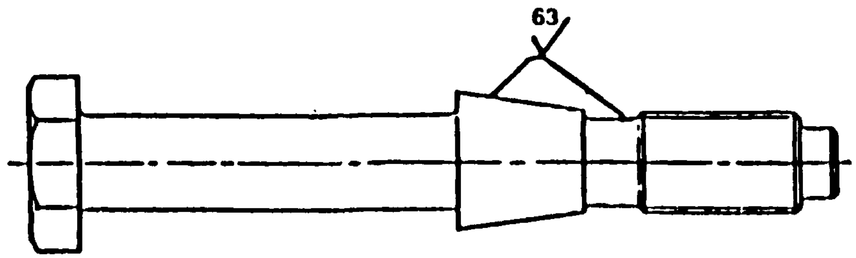


Figure 13. Schematic of bolt design. Surface finish is specified as 125 microinches, except the two areas indicated where the finish is 63 microinches.

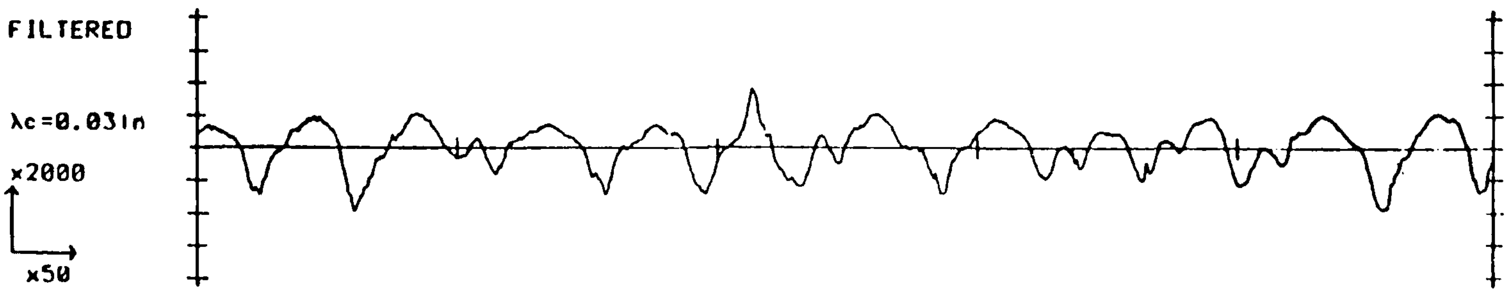


Figure 14. Topography traversed by profilometer on Area 1(refer to Table 1). The RMS roughness value obtained was 68 microinches.

Table 1. ROOT MEAN SQUARE (RMS) ROUGHNESS VALUES OF THREE SELECTED AREAS

Surface	Roughness (RMS) (u in.)
Area 1	68
Area 2	64
Area 3	70

Chemical Analysis

The pitch horn bolt was specified to be fabricated from 4340 steel conforming to the requirements established in AMS 6414 entitled "Steel Bars, Forgings, and Tubing." Atomic absorption (AA) and inductively coupled argon plasma emission spectrometry (ICAP) were used to determine the chemical composition of the alloy. The carbon and sulfur content was analyzed by the LECO Combustion Method. These analytical techniques quantify slight differences in chemistry within a large sample that may be undetected or misinterpreted by energy dispersive spectroscopy (EDS). Five grams of the bolt material was obtained from a transverse cross section, thereby representing the overall composition of the component. EDS utilizes a small microprobe which scans an area ranging from approximately 15 A^{o} to 2 mm. The depth of penetration is about 1 micron. Therefore, EDS was not intended to be a bulk analysis technique and should be used with caution if applied in this manner. The specified ranges for 4340 steel have been included in Table 2 for comparative purposes. The compositional ranges of the material under investigation compared favorably with published values.

Table 2. COMPARISON OF CHEMISTRIES

Element	C	MN	Si	P	S	Cr	Ni	Mo	Cu
AMS 6414	0.38-0.43	0.60-0.90	0.15-0.35	0.015 Max	0.015 Max	0.70-0.90	1.65-2.00	0.20-0.30	0.35 Max
Bolt No. 3	0.387	0.71	0.28	0.007	0.002	0.82	1.76	0.28	0.067

Hardness Testing

Rockwell "C" Scale
150 Kg. Load
Diamond Cone Penetrator

The engineering drawing of the pitch horn bolt specified a minimum tensile strength range of 180 to 200 ksi which converted to an approximate hardness level of Rc 39-43. Macrohardness measurements were taken on transverse cross sections of the bolt above the conical region, as shown schematically in Figures 15 and 16. The results of this test did not reveal evidence of any regions that displayed unusually higher or lower degrees of hardness, which may occur if the material had been locally heated. The average value of all the measurements taken did show that the material was hardened to the upper limit of the acceptable range (refer to Table 3).

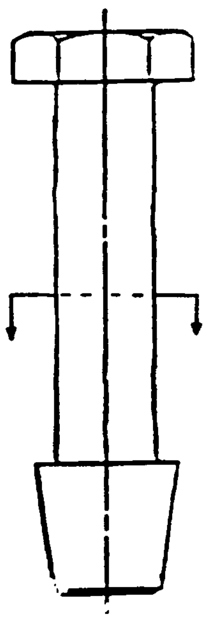


Figure 15. Indicates the area where the bolt was sectioned for hardness testing.

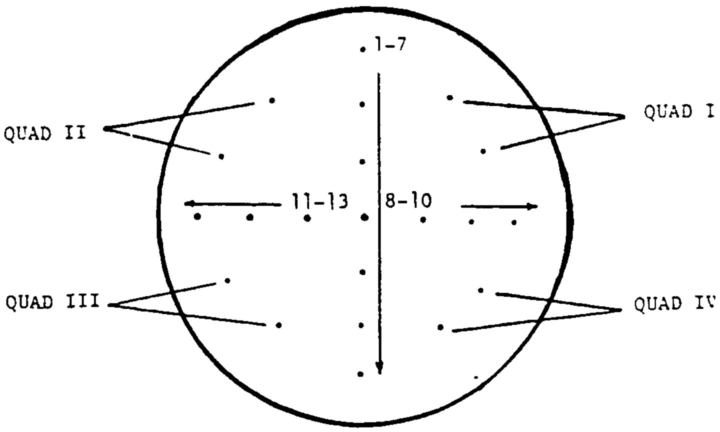


Figure 16. Shows the transverse cross section of the bolt and locations where hardness measurements were taken.

Table 3. MACROHARDNESS MEASUREMENTS

Bolt No. 3	
No. of Readings	HRC Values
1	42.6
2	43.8
3	44.0
4	44.1
5	44.1
6	43.3
7	43.6
8	44.0
9	44.0
10	43.3
11	44.3
12	43.8
13	42.1
Quad I	43.5 43.7
Quad II	43.3 43.8
Quad III	44.0 44.1
Quad IV	43.9 43.9
Avg.	43.7
S.D.	0.54

Metallographic Examination

A transverse cross section of the bolt was taken adjacent to the failure and prepared for metallographic examination. A 1% Nital etchant revealed a typical tempered martensitic structure, as shown in Figure 17. Close examination of the microstructure near the crack initiation site and areas near the fracture were conducted in order to detect any possible structural changes that may have occurred during fabrication or in service. There were no signs of structural changes or any regions that contained unusual precipitation or coagulation of carbides. In addition, the material was relatively "clean" having no large inclusions or inherent material defects.

Figure 18 contains the transverse section of the bolt utilized for macrohardness testing in the as-polished condition. The cadmium plating was inspected and measured. The average plating thickness was approximately 0.0018 in., and appeared to be intact in the areas examined which were above the conical section of the bolt. The areas adjacent to the fracture contained only sparse traces of the plating that had undoubtedly been damaged in service.

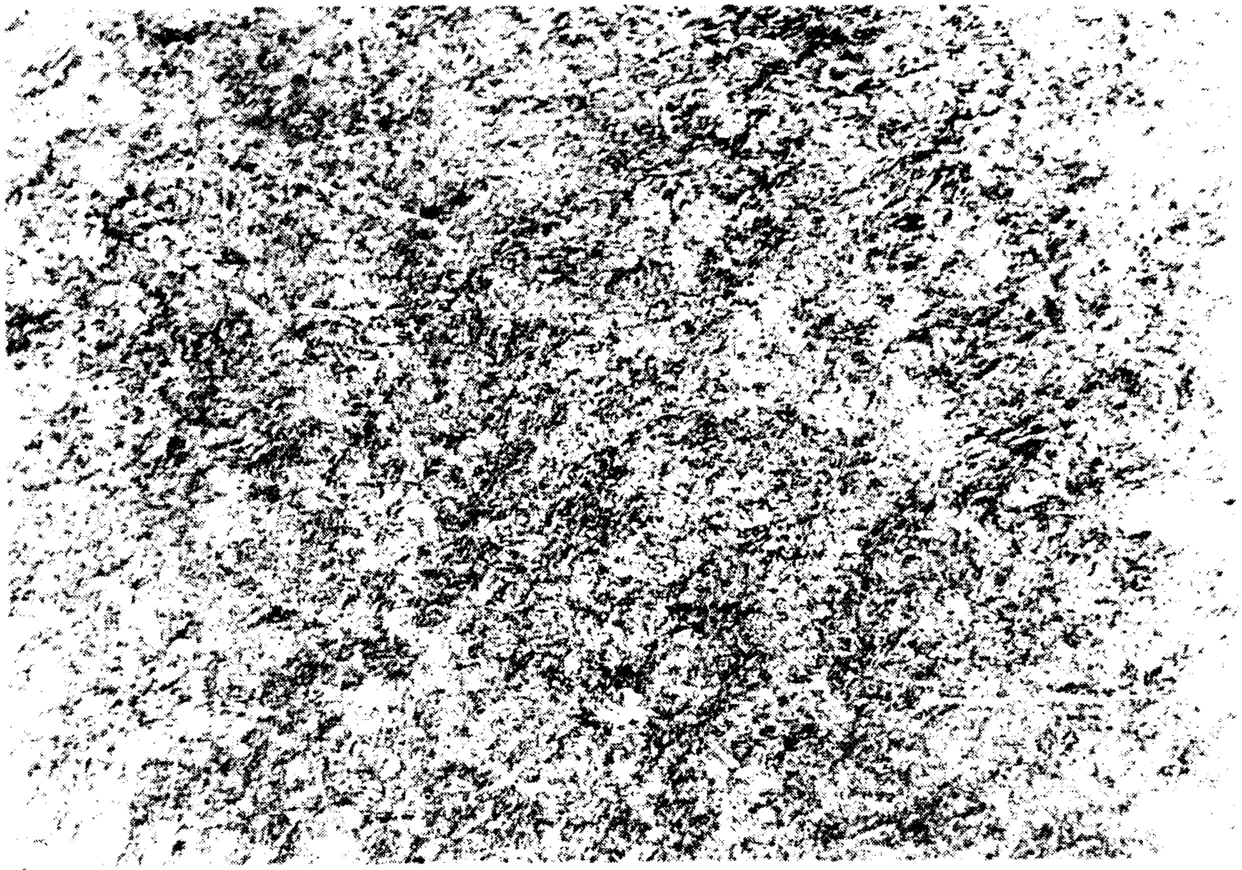
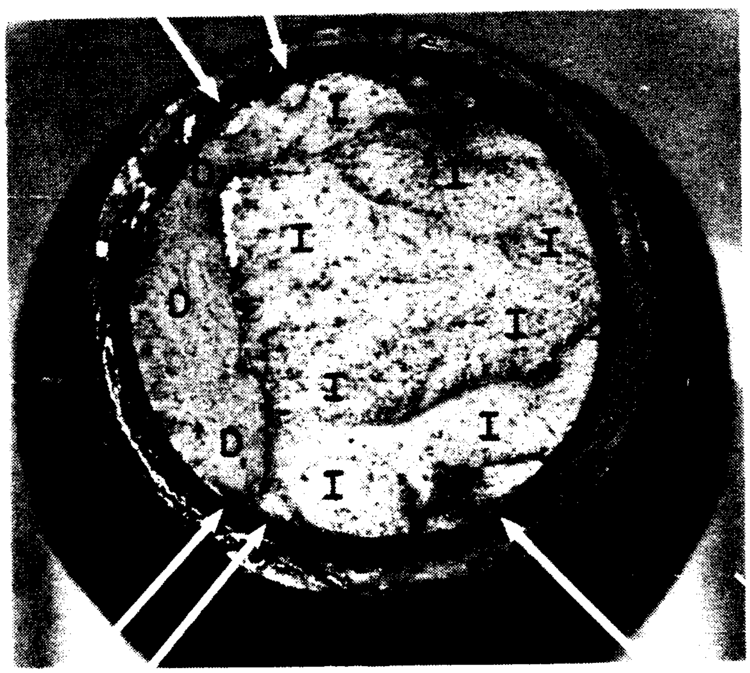


Figure 17. Shows the representative microstructure of the bolt which was tempered martensite. MAG. 500X.

Figure 18. Contains as-polished transverse section of the component containing the cadmium plating. MAG. 500X.

Fractography

The pitch horn bolt sheared completely in half below the conical section at the threaded portion of the component while in service. Since the threaded section below the fracture which contained the nut was missing upon disassembly, only one fracture face could be examined. The scanning electron microscope (SEM) was utilized to identify the failure mode in each fracture zone identified in Figure 19. An enlargement of the fracture surface of the bolt is contained in Figure 20. Figure 19 was taken with an optical microscope, while Figure 20 is a SEM macrograph provided for comparative purposes. In many instances certain macroscopic features of the fracture are highlighted better with reflective light, such as corrosion. The cadmium plating circumventing the fracture was blistered and worn away entirely in numerous locations exposing a bare metal surface to the environment. This condition is ideal for Stress Corrosion Cracking (SCC) to occur. The arrows in both fractographs identify crack origins. These areas assumed a geometry indicative of a "thumbnail" crack, so-called because of their resemblance to a human thumbnail. The fracture path was complex and not easily discernable. The material did not exhibit much plasticity during fracture which was anticipated from an embrittlement type failure. There were also several regions darkened by corrosion that are more readily visible in Figure 19. Multiple crack origin sites are a common feature associated with SCC, whereas a failure attributed to Hydrogen Embrittlement, in which hydrogen had diffused into the material during electroplating would normally consist of a single large crack. In addition, HE fracture surfaces tend to be free of heavy oxides and corrosion in contrast to surfaces which are the result of SCC because, in the latter case, these failures are environmentally induced.



KEY

I = intergranular fracture

D = ductile fracture

Figure 19. Optical macrograph of the fracture surface showing the various crack propagation zones. MAG. 7.5X.

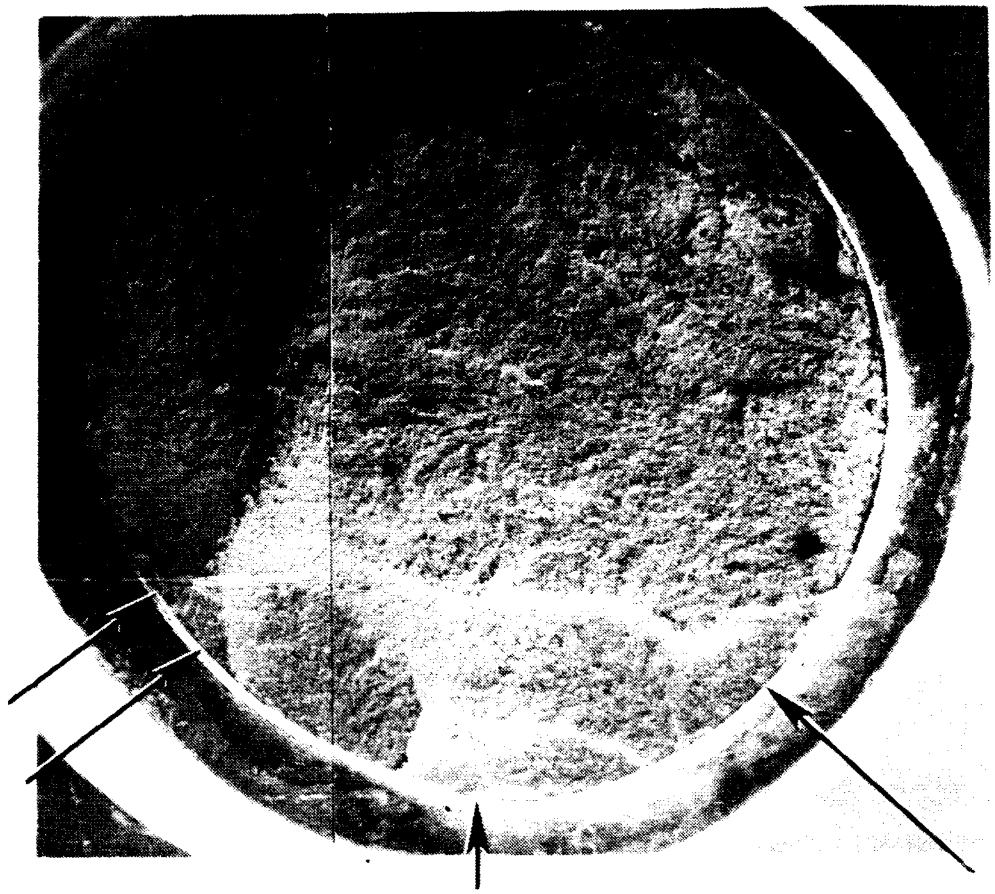


Figure 20. SEM fractograph comparing macroscopic features of the surface with those of Figure 19. MAG. 10X.

Figure 21 shows one of the "thumbnail" cracks covered with a dark layer of corrosion making it highly distinguishable. The shape of this type of fracture usually suggests a single point crack origin, such as a surface defect or machining mark. The failure did occur at the machined radius which was a stress concentration area, but more significantly, corrosion pits most likely initiated the cracks, as shown in Figure 22. The morphology within the "thumbnail" crack was different than the surrounding fracture surface. Closer examination revealed that the failure mode within this region was intergranular, as shown in Figure 23, with some evidence of secondary cracking. SCC fractures in high-strength, quench, and tempered 4340 steel occur primarily by intergranular decohesion. The areas beyond the "thumbnail" cracks exhibited a mixed topography of ductile dimples, as shown in Figure 24, and also intergranular cracking before the onset of final fast fracture. Figure 25 contains the transitional zone of a crack which progressed from an intergranular mode of failure to one of ductility.

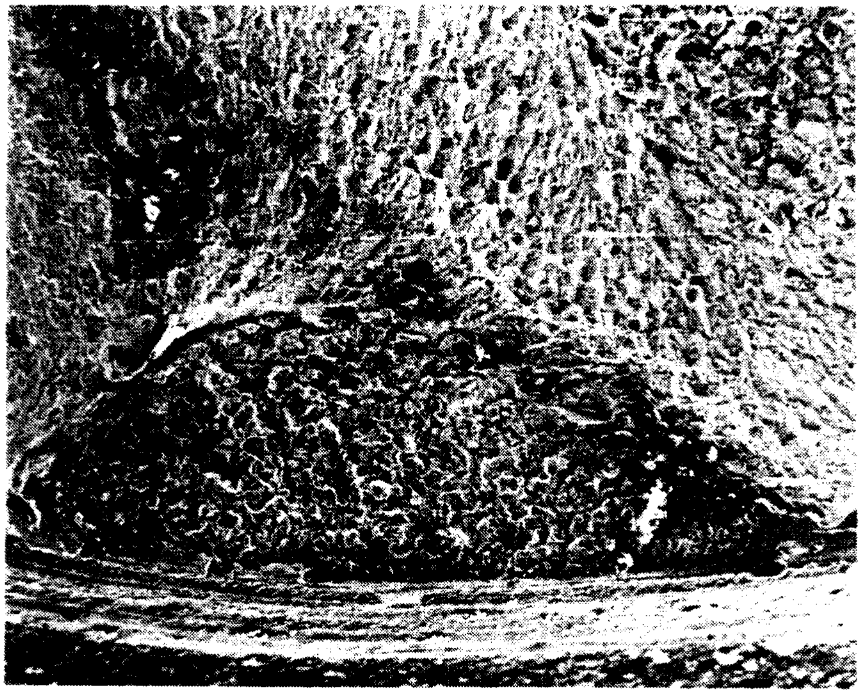


Figure 21. SEM containing a "thumbnail" crack. MAG. 75X.

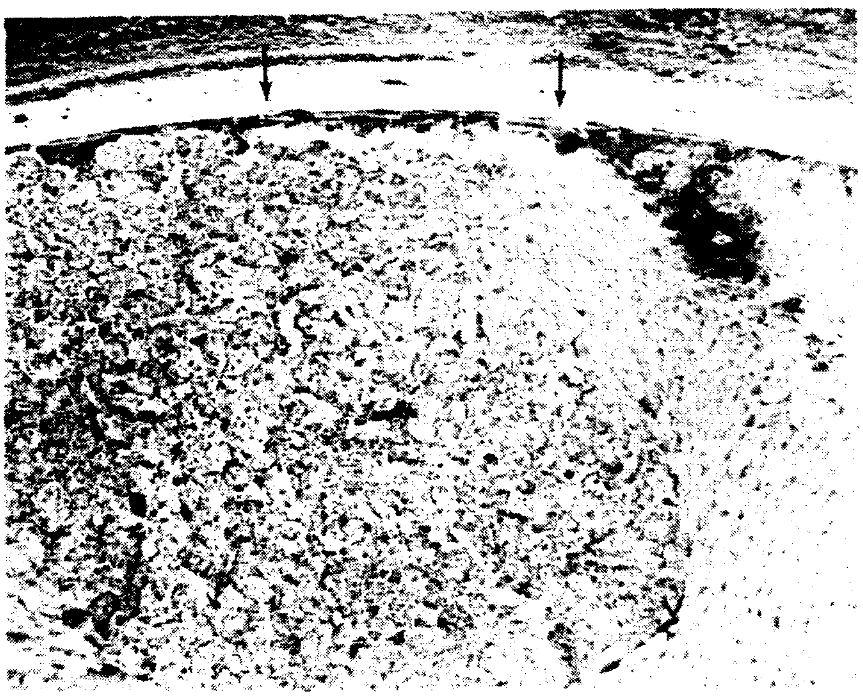


Figure 22. SEM showing corrosion pits adjacent to the fracture (designated by the arrows). MAG. 50X.

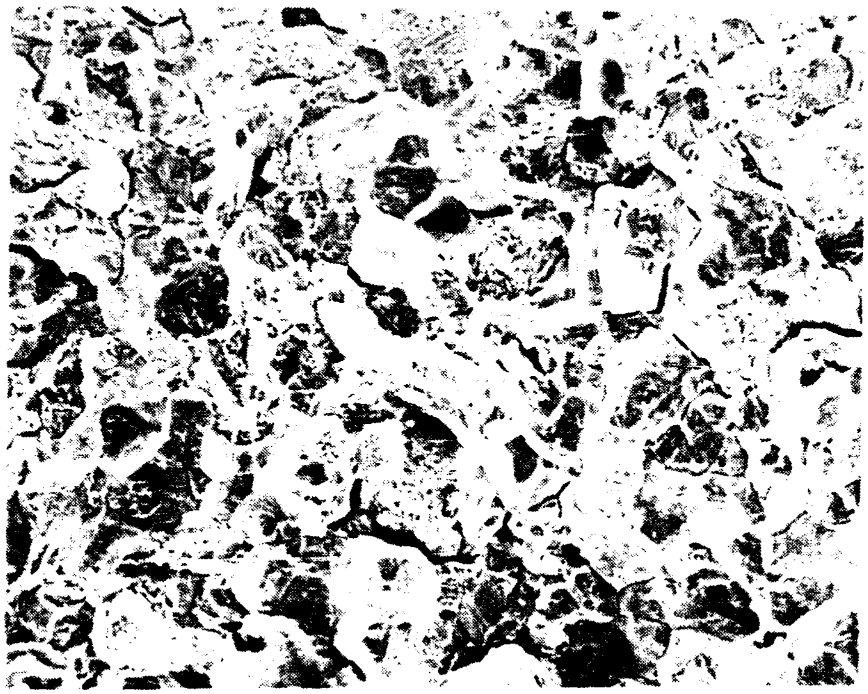


Figure 23. SEM within the "thumbnail" verifying that the failure mode was intergranular. MAG. 500X.

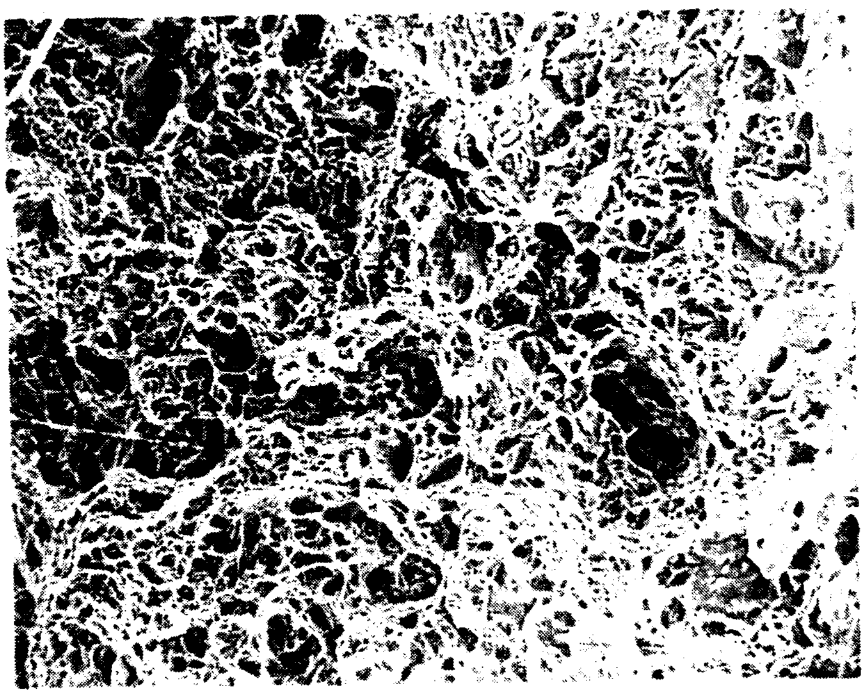


Figure 24. SEM representative of the fast fracture zones with a predominantly ductile dimpled surface morphology. MAG. 1KX

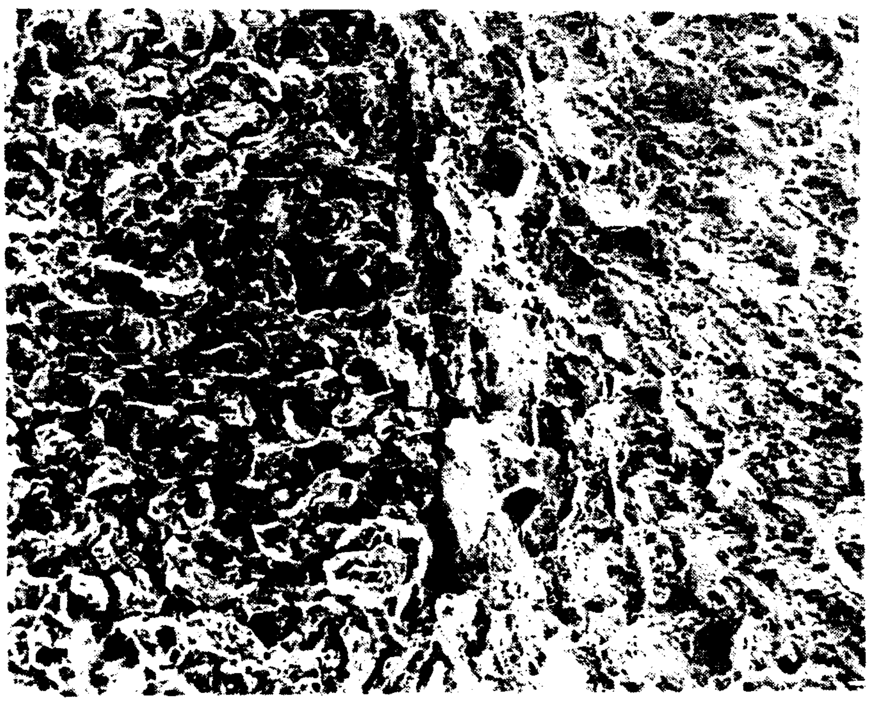


Figure 25 SEM of a failure mode transition from intergranular to ductile dimples. MAG. 200X

Energy dispersive spectroscopy (EDS) was utilized to characterize the composition of the dark corrosion layer which covered the "thumbnail" cracks. Figures 26 and 27 reveal the spectra of these regions which consisted of those elements associated with the type of steel under investigation, such as Fe, S, and Si, as well as oxygen which is indicative of a corrosion product. The Cd peaks represent traces of the cadmium plating while C and Ca may be attributed to surface oils, lubricants, or greases. Au and Pd were present because the fracture surface of the bolt had been sputtered with a fine layer of these elements for examination purposes under the SEM. Titanium dioxide is commonly used as a coloring agent in paint pigment and also exists in some lubricants. The most significant finding was that of Cl which may be found in large concentrations as a result of pitting or crevice corrosion. The environment within a pit or crevice becomes acidic with time and the pH value can decrease to approximately 1.5 to 1.0 while the pH of the bulk solution remains neutral. Since these forms of corrosion are autocatalytic in nature the degree of metal dissolution within these regions increases as does hydrogen evolution. This alteration of the bulk environment combined with internal or externally applied stress allows the formation of SCC.

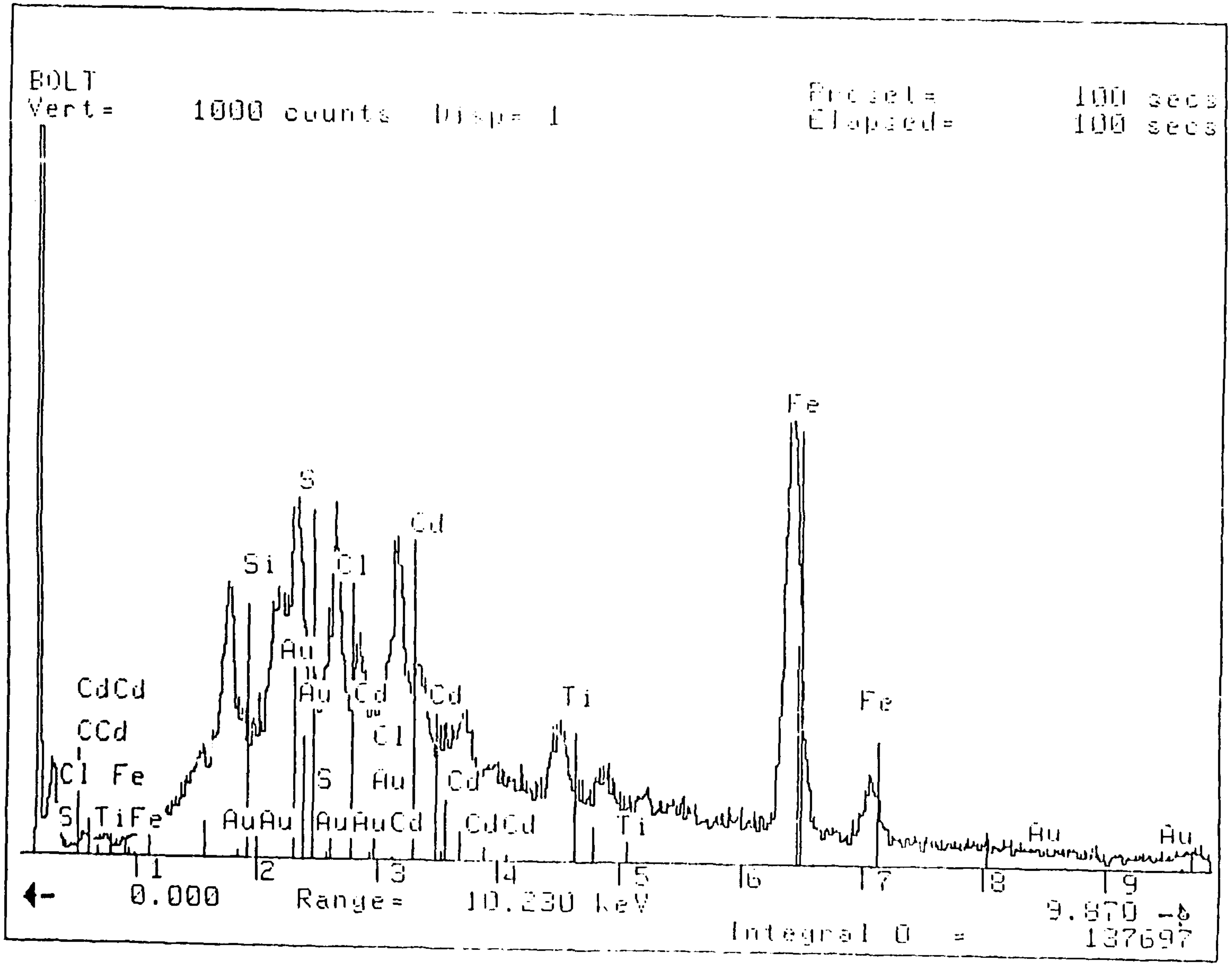


Figure 26. EDS spectra within the "thumbnail" crack region.

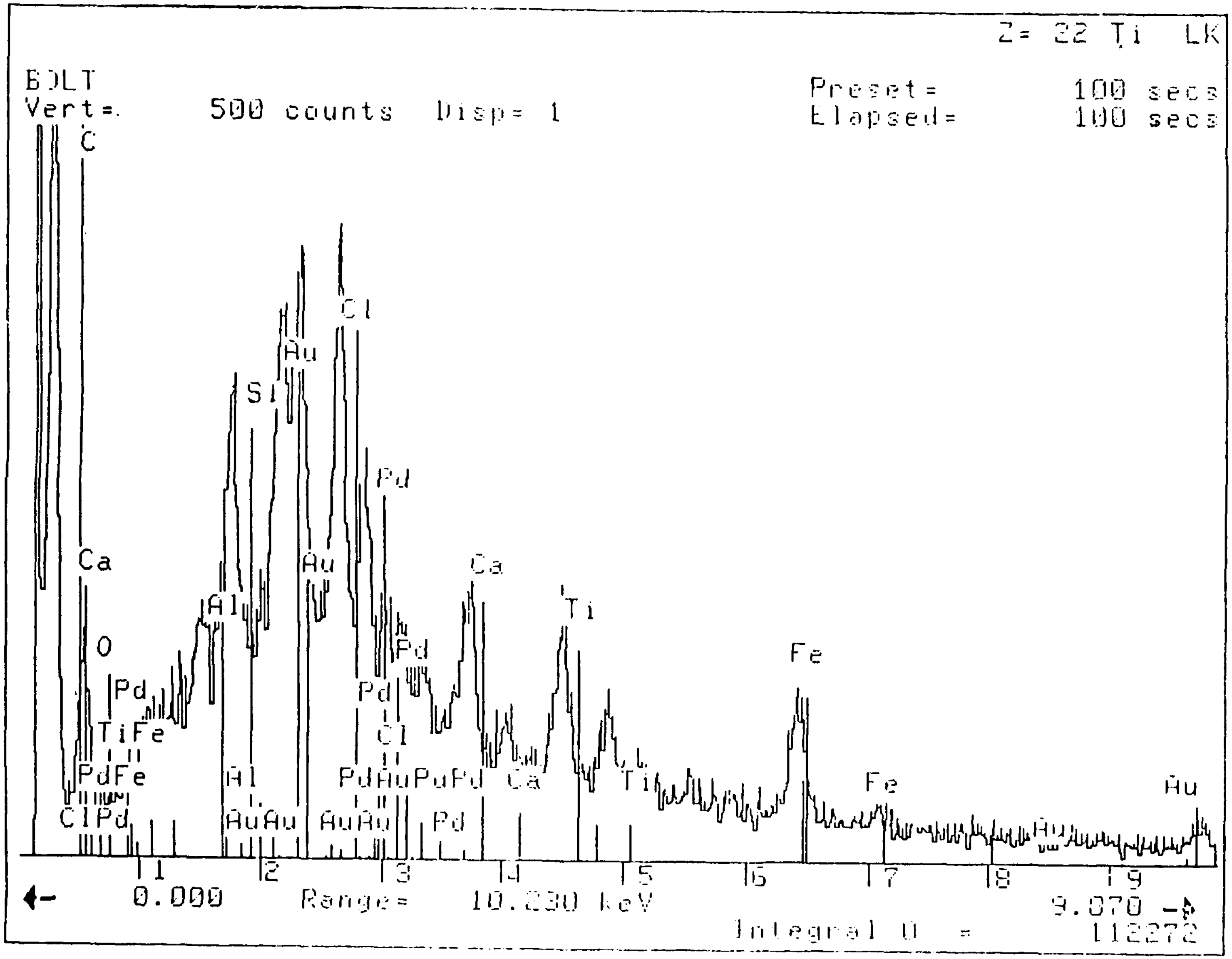


Figure 27. EDS spectra within the "thumbnail" crack region.

DISCUSSION

Sources of Hydrogen

The important issue that was addressed when determining the cause and prevention of this failure was isolating the probable sources of hydrogen which lead to the premature fracture of the component. Only then could a viable solution to the problem be established. Time-delayed embrittlement failures may be caused by the residual atomic hydrogen in the material from:

- The initial steel making or melting process
- Subsequent manufacture (such as electroplating or pickling)
- The service conditions (i.e., corrosion)

The two most likely sources of hydrogen in this investigation were:

1. The electroplating process
2. The service environment

The characteristics and influence of these hydrogen sources on the failure mechanism are outlined in the proceeding discussion.

The Electroplating Process

It is well documented that nascent hydrogen can permeate into 4340 steel during electroplating, possibly leading to embrittlement and catastrophic failure of a stressed structural component, such as the pitch horn bolt, while in service.* Hydrogen embrittlement (HE) of this nature occurs frequently in high strength steel fasteners. These failures can be difficult to distinguish from SCC fractures, particularly when the environment is also a source of hydrogen. Both mechanisms usually result in faceted, intergranular fracture origins in this type of material. This mode of failure was observed within the various crack initiation sites examined. Each region displayed a fracture surface that resulted from intergranular decohesion. However, from an investigative perspective, if hydrogen pickup was solely a result of the steel making process or the electroplating procedure, many more instances of failure would have been expected. One of the reasons is because either a great amount of material or a large number of components would be affected. Steel is produced in batches weighing many tons, while fasteners are usually plated in large quantities at one time.

Other factors which must be known before the exact source of hydrogen can be isolated are the age of the failed components and their corresponding manufacturers. The pitch horn bolt under investigation was thought to have been installed on a fielded aircraft for an extended period of time. The bolt was considered to have been in service for at least a year and possibly as many as 15 years. This information was based upon certain traceable aspects of the component, such as recorded flight time prior to failure, the manufacturer's code, and if the bolt contained locating holes in the top of the head and/or the bottom of the threaded portion.

*Failure Mechanisms and Related Environmental Factors. ASM Metal Handbook, Failure Analysis and Prevention, v. 11, p. 126.

The significance of this data is that HE failures resulting from hydrogen diffusion into the material during electroplating will normally occur within a short period; typically, only the time needed by hydrogen to migrate into areas of high stress concentration and induce embrittlement. This deduction takes into account all of the metallurgical factors, loading conditions, and residual stresses within the material after fabrication. There are many instances where 4340 steel fasteners have failed by HE even before being installed in service.

In addition, if the pitch horn bolt failed due to HE from the electroplating process, then it would be conceivable that the defective part could be traced back to a single manufacturer. However, pitch horn bolts fabricated by different manufacturers have also recently failed in service at the same time that this investigation was being conducted.

The Environment

When metal becomes exposed to moist air or seawater, atomic hydrogen can be generated at the surface (cathode) by the dissociation of water due to the corrosion process. The area where the electrochemical attack is taking place is referred to as the anode. In contrast to other forms of corrosion, HE can occur in service when the part is adequately protected from corrosion, perhaps by a plating, or when the component itself is not even being attacked. Corrosion can take place on the mating part (such as the nut or the bushing) and the hydrogen generated at this location could migrate into the bolt and cause embrittlement under the proper conditions. SCC caused by the mechanism of HE can occur at any time within the service life of the component. The three general requirements for this type of failure are as follows:

1. A material susceptible to SCC (i.e., 4340 steel)
2. A corrosive environment (moist air)
3. An adequate stress level (residual or applied)

Therefore, this type of failure is not constrained to any specific fabrication process and the source of hydrogen (water) is easily acquired and abundant out in the field.

Stress Corrosion Cracking

Stress corrosion cracking (SCC) is the result of combined interaction of mechanical stress and corrosion where neither factor acting independently or alternately would initiate and propagate a crack in the pitch horn bolt until final catastrophic failure occurred. The stresses required to cause SCC are often times quite minimal, especially in high strength steels which have a considerably low value of K_{ISCC}. In order for SCC to occur under a sustained load, the stress intensity must exceed the stress corrosion threshold K_{ISCC}. The K_{ISCC} is influenced by the type of material, its condition, and the corrosive environment above which stress corrosion crack propagation occurs and below which the material is immune from SCC. It is important to realize that the stresses required to initiate this type of failure were most likely well below the yield stress and could have been externally applied or residual.

CONCLUSIONS

1. The failure of the pitch horn bolt was attributed to SCC based upon the results presented within the context of this report and from historical data collected during the investigation.

2. Visual inspection and light optical microscopy revealed evidence of corrosion pitting in adjacent regions to the fracture. In these locations the cadmium plating had been completely worn away during service.

3. A Mitutoyo Surftest Analyzer was used to measure the surface finish along the upper bolt shank in three locations. The results showed that the surface profile was within the specified range.

4. A chemical analysis utilizing Atomic Absorption (AA), Inductively Couple Argon Plasma Spectrometry (ICAP) and the LECO Combustion Method verified that the pitch horn bolt was fabricated from 4340 steel according to the requirements established in AMS 6414.

5. Hardness measurements taken on transverse cross sections of the bolt adjacent to the fracture indicated that the material was hardened to the upper limit of the acceptable range as designated on the engineering drawing.

6. Metallographic examination revealed that the microstructure was tempered martensite, indicative of the heat treating process utilized. There were no large inclusions or any unusual microstructural features observed, such as decarburization or grain refinement.

7. Fractographic examination utilizing the SEM showed multiple crack origins which assumed a "thumbnail" shape and displayed surface morphologies which resulted from intergranular decohesion. Many of these crack sites were initiated by corrosion pits. Energy dispersing spectroscopy (EDS) performed on areas covered with a dark corrosion layer showed the presence of chlorides. Fast fracture occurred in a ductile manner, which was confirmed by a dimpled topography in these regions.

CAUSE OF FAILURE

It has been established that the principal SCC mechanism in high strength steels subjected to typical atmospheric conditions is hydrogen embrittlement. The basic process which lead to SCC in this case involved a series of events that began with the rupture of the protective cadmium plated surface of the bolt in many locations which may have occurred during installation or in service, resulting in numerous crack origins. This was followed by metal dissolution during exposure to the environment and eventually a pit or crevice formed where a crack initiated and propagated. Hydrogen ions were a product of the electrochemical corrosion reaction between the exposed metal and the electrolyte (humid air, salt water, etc.). Subsequent reduction of the hydrogen ions resulted in the formation of hydrogen gas and/or the diffusion of atomic hydrogen into the metal. Once hydrogen diffused into the steel, it migrated to areas of high stress concentration, such as corrosion pits, inclusions, voids, or, in this instance, the crack tips. The triaxial state of stress combined with the absorption of hydrogen and the stress concentration at the crack tip provided a driving force for further crack propagation by the mechanism of hydrogen embrittlement. Eventually, as the process of electrochemical attack, subsequent absorption of hydrogen into the various crack tip regions and crack propagation continued, the stress parameters of the material were exceeded and final catastrophic failure of the component occurred.

RECOMMENDATIONS

It is not the intent of this investigation to offer specific guidance on preventive measures against SCC of the pitch horn bolt. This undertaking would require an extensive analysis of many factors which includes, but is not limited to, the following:

- Service conditions
- Resonant frequency of entire assembly
- Mating components to safeguard against galvanic effects
- Maximum applied loads
- Cost considerations
- Manufacturing lead times
- Material availability and machinability

There are, however, general preventive steps which can be implemented immediately. Since SCC can only occur if three basic requirements are satisfied, if one of them is eliminated the problem is solved.

Criteria of Stress Corrosion Cracking

1. A material susceptible to SCC
2. A corrosive environment
3. A sufficient stress

Manufacturing Controls

Although the SCC mechanism that caused the bolt failure was attributed to hydrogen which migrated into the material as a result of corrosion, preventive measures should be adhered to during manufacturing to avoid unnecessary hydrogen pickup during these operations. Hydrogen that diffuses into the steel while it is being electrolytically cadmium plated could later combine with the hydrogen, which was a result of the corrosion process increasing the overall concentration within the material significantly enough to cause premature failure.

Electroplating

Plating solutions and conditions selected to produce a high-cathode efficiency should be incorporated. This minimizes the amount of hydrogen generated at the surface.

Hydrogen diffuses less readily through cadmium than other metallic platings and although conventional bright cadmium deposited from cyanide baths is preferred due to its shiny, reflective appearance, this plating is a barrier to hydrogen diffusion. In addition, "brighteners" which are added to these plating baths can dissociate forming atomic hydrogen. Therefore, low embrittlement baths are used for high strength steels which produce a dull, more porous coating that allows hydrogen diffusion upon baking. These platings are often sealed since they are not as protective as bright cadmium coatings.

Baking of the components should commence within one hour after plating. The bake time should remain 24 hours minimum, at a temperature of 385°F.

PREVENTION MEASURES

Short-Term Prevention Plan

- Insure integrity of surface coatings
- Never electrolytically replate bolts
- Inspect radii for deep machining marks

A short-term prevention plan would be to insure that the protective coatings on the pitch horn bolt remain intact to combat the formation of corrosion pits, which act as crack initiation sites. In addition, the corrosion reaction is a source of atomic hydrogen. Inspect all bolt radii for deep machining marks which form stress concentration regions and act as SCC initiation sites.

Long-Term Prevention Plan

- Redesign bolt
- Utilize alternative material (higher K_{ISCC} value)
- Specify MIL-C-8837 (vacuum deposited cadmium)

A long-term solution to the problem of HE or hydrogen assisted SCC would be to redesign the bolt to minimize stress concentration areas. In addition, the component could be fabricated from an alternative material that has a higher value of K_{ISCC}. The K_{ISCC} for 4340 steel is $\sqrt{26 \text{ ksi in.}}$ at a Ftu of 195 ksi. It is strongly recommended that MIL-C-8837 (Coating, Cadmium - Vacuum Deposited) be incorporated in place of any specification containing the electrolytic method for cadmium plating. The vacuum deposition process will prevent HE of the material during plating that can be induced by the electrolytic plating process.

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